DESCRIPTION

MICRO ACTUATOR AND DEVICE HAVING MICRO ACTUATOR

TECHNICAL FIELD

[0001]   The present invention relates to a microactuator capable of tilt and vertical displacement, as well as an apparatus incorporating such microactuators.

BACKGROUND ART

[0002]   Various microactuators have been produced by using MEMS (Micro Electro Mechanical System) techniques, and applications of microactuators to various fields such as optics, high-frequency circuits, and biotechnology are expected.   For example, in the field of adaptive optics, micromirror arrays for controlling the wave front of light are being developed.   In such applications, in order to smoothly control the wave front of light, it is effective to cause each light reflecting surface to have a tilt as well as a vertical displacement relative to a base.

[0003] An example of a microactuator which is capable of such tilt and vertical displacement is disclosed in Non-patent Document 1. FIG. **10** is a perspective view schematically showing a microactuator **1000** disclosed in Non-patent Document 1.

[0004] The movable electrode **100** is supported at its outer periphery by three elastic beams **101a**, **101b**, and **101c**. Moreover, the movable electrode **100** opposes three stationary electrodes **102a**, **102b**, and **102c**. The stationary electrodes **102a**, **102b**, and **102c** are provided in such a manner that a driving voltage can independently be applied to each of them, whereby a potential difference with the movable electrode **100** is obtained. As a result, an electrostatic force is generated in a direction of pulling the movable electrode **100**.

[0005] If equal driving voltages are set for the stationary electrodes **102a** to **102c**, the movable electrode **100** makes a vertical displacement in the lower direction, without tilting. If these driving voltages are made different, the movable electrode **100** makes a vertical displacement in the

lower direction while tilting in the desired direction. Thus, the movable electrode 100 is capable of making a vertical displacement in the lower direction as well as having a bi-axial tilt.

[0006]   Since the mirror 103 is attached to the movable electrode 100 at an attachment section 104, the displacement of the movable electrode 100 in itself governs the displacement of the mirror 103.

Non-patent Document 1: U.Srinivasan, et al., "FluidicSelf-Assembly of Micromirrors Onto Microactuators Using Capillary Forces", IEEE Journal on Selected Topics in Quantum Electronics, Vol. 8, No.1, pp.4-11 (January, 2002)

DISCLOSURE OF INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

[0007]   However, the aforementioned microactuator 1000 has a problem in that there is a large non-diagonality in the relationship between driving signals for the stationary electrodes and the mirror displacement. As used herein, non-diagonality means, when a predetermined voltage is applied to

a given stationary electrode so that one end of the movable electrode **100** opposing that stationary electrode makes a displacement along the vertical direction, an end portion of the movable electrode **100** opposing another stationary electrode making a displacement along the vertical direction.

[0008] This problem will be described with reference to FIG. **11**. FIG. **11** is a diagram showing an operation of the microactuator **1000**. Since FIG. **11** is a schematic cross-sectional view of the microactuator **1000**, only the movable electrode **100**, two elastic beams **101a** and **101b**, and two stationary electrodes **102a** and **102b** are illustrated therein. A point of application **a** of a driving force that is exerted by the stationary electrode **102a** on the movable electrode **100** is a point on an axis which extends through the center of a region of the stationary electrode **102a** where the driving force occurs and which is perpendicular to the stationary electrode **102a**. A point of application **b** of a driving force that is exerted by the stationary electrode **102b** on the movable electrode **100** is a point on an axis which extends through the center of a region of the stationary electrode

4

102b where the driving force occurs and which is perpendicular to the stationary electrode **102b**.

[0009] Herein, a case will be described where a predetermined voltage is applied only to the stationary electrode **102a** to pull the movable electrode **100**. The stationary electrode **102a** generates a driving force F, and at the point of application **a**, the movable electrode **100** is displaced by δ along the vertical direction. At this time, the movable electrode **100** is also displaced along the vertical direction by δ ' at the point of application **b** opposing the stationary electrode **102b**, which is not generating driving force. The value δ '/δ of the ratio between the displacement δ ' and the displacement δ will be used as an index of degree of non-diagonality.

[0010] From the standpoint of controlling the posture of the movable electrode **100**, such non-diagonality should be as small as possible. If the non-diagonality is sufficiently small relative to the target resolution of displacement, the displacements of the movable electrode **100** at the points of application **a** and **b** can be independently controlled with the

applied voltages on the corresponding stationary electrodes, and therefore the structure of the control device can be simplified. Moreover, even in the case of performing control for correcting displacements (e.g., δ') associated with non-diagonality, the accuracy improvements and simplification of control will become easier as the non-diagonality becomes smaller. Especially in the case of electrostatic driving, driving force can only occur in a pulling direction, and therefore it would be difficult to perform correction control in a direction of rendering the size of δ' back to zero. Moreover, in the case where the microactuator has large fluctuations in characteristics, the amount of data for correcting displacements associated with non-diagonality will become enormous. In particular, in the case where the aforementioned non-diagonality is large in an apparatus having a large number of microactuators (e.g., a micromirror array), the amount of data for correcting the displacements associated with non-diagonality will be enormous. This will cause a tremendous increase in cost and a decrease in the driving speed of the microactuators. From such a

perspective, it is desirable that the non-diagonality is as small as possible.

[0011] However, as is clear from FIG. **10** and FIG. **11**, in any structure in which the movable electrode **100** is supported at its outer periphery, with stationary electrodes being formed inside, the driving force F generated by one stationary electrode **102a** will cause all positions on the movable electrode **100** to be displaced in the lower direction, and therefore there is a very large non-diagonality. In terms of accuracy improvements and simplification of correction control, it would be desirable that the non-diagonality δ'/δ is 1/3 or less. However, in accordance with the structure of the conventional microactuator **1000**, it has been very difficult to reduce the non-diagonality to 1/3 or less, even with design optimization.

[0012] The present invention has been made in view of the aforementioned problems, and an objective thereof is to provide a microactuator whose non-diagonality between driving force and displacement of a movable section is reduced, and an apparatus incorporating such microactuators.

MEANS FOR SOLVING THE PROBLEMS

[0013]   A microactuator according to the present invention

is characterized in that the microactuator comprises: a base;

a movable section capable of displacement relative to the

base; an elastic supporting member for supporting the movable

section so as to allow the movable section to make a

displacement relative to the base along a vertical direction

and a tilt relative to the base; and a plurality of driving

sections for causing the movable section to be displaced

relative to the base, wherein, the plurality of driving

sections include a first driving section and a second driving

section, and the elastic supporting member supports the

movable section at a position intermediate between a first

point of application of a first driving force which is

exerted by the first driving section on the movable section

and a second point of application of a second driving force

which is exerted by the second driving section on the movable

section, and assuming that: a spring modulus of a restoring

force occurring in the elastic supporting member responsive

to a displacement of the movable section relative to the base along the vertical direction is kz(N/m); a spring modulus of a restoration torque occurring in the elastic supporting member responsive to a tilt angle of the movable section relative to the base is kr(Nm/rad); and a distance between the first point of application and the second point of application is 2L(m), kz, kr, and L satisfy the relationship of: $0.5 \leqq L^2 \cdot kz/kr \leqq 2$.

【0014】 A microactuator according to the present invention is characterized in that the microactuator comprises: a base; a movable section capable of displacement relative to the base; an elastic supporting member for supporting the movable section so as to allow the movable section to make a displacement relative to the base along a vertical direction and a bi-axial tilt relative to the base; and a plurality of driving sections for causing the movable section to be displaced relative to the base, wherein, the elastic supporting member supports the movable section at a position surrounded by a plurality of points of application at which driving forces exerted by the plurality of driving sections

on the movable section are applied, and assuming that: a spring modulus of a restoring force occurring in the elastic supporting member responsive to a displacement of the movable section relative to the base along the vertical direction is $kz(N/m)$; spring moduli of restoration torques occurring in the elastic supporting member responsive to a tilt angle of the bi-axial tilt of the movable section are $krx(Nm/rad)$ and $kry(Nm/rad)$; and a distance between each of the plurality of points of application and the position at which the elastic supporting member supports the movable section is $R(m)$, kz, krx, kry, and R satisfy the relationships of: $1 \leqq R^2 \cdot kz/krx \leqq 5$; $1 \leqq R^2 \cdot kz/kry \leqq 5$; and $0.67 \leqq krx/kry \leqq 1.5$.

[0015]   In one embodiment, the elastic supporting member supports a generally central portion of the movable section.

[0016]   In one embodiment, at least a portion of the movable section is electrically conductive; each of the plurality of driving sections includes an electrode opposing the movable section; and each of the plurality of driving sections drives the movable section with an electrostatic force occurring between the movable section and the

10

electrode.

[0017]   In one embodiment, the plurality of driving sections are disposed so as to be generally symmetric around an axis which extends through the position at which the elastic supporting member supports the movable section and which is perpendicular to the base.

[0018]   In one embodiment, the elastic supporting member comprises a first end portion connected to the base and a second end portion connected to the movable section, and assuming that a distance between the first end portion and the second end portion is H, H and R satisfy the relationship of: $0.8 \leqq H/R \leqq 1.6$.

[0019]   In one embodiment, a distance between the first end portion and a central portion of the movable section is longer than a distance between the second end portion and the central portion of the movable section.

[0020]   In one embodiment, the elastic supporting member comprises a beam, and the beam includes a turn-back portion at which a direction in which the beam extends is reversed.

[0021]   In one embodiment, the distance between the turn-

11

back portion and the central portion of the movable section is longer than the distance between a position at which the elastic supporting member is connected to the base and a central portion of the movable section.

[0022] In one embodiment, when one of the plurality of driving sections drives the movable section so that one end of the movable section is displaced in a direction of approaching the base, another end of the movable section is displaced in a direction of becoming more distant from the base.

[0023] In one embodiment, kz, kr, and L satisfy the relationship of: $1 \leqq L^2 \cdot kz/kr$.

[0024] In one embodiment, kz, krx, kry, and R satisfy the relationships of: $2 \leqq R^2 \cdot kz/krx$; and $2 \leqq R^2 \cdot kz/kry$.

[0025] An apparatus according to the present invention is characterized in that the apparatus comprises a plurality of aforementioned microactuators, wherein the plurality of microactuators share the base with one another.

[0026] An apparatus according to the present invention is characterized in that the apparatus comprises a plurality of

aforementioned microactuators, wherein, the plurality of microactuators share the base with one another, and assuming that a pitch between adjoining microactuators among the plurality of microactuators is P(m), P and R satisfy the relationship of: $0.29 \leqq R/P \leqq 0.37$.

[0027] In one embodiment, the apparatus further comprises a control section for outputting a control signal to the plurality of driving sections to control the displacement of the movable section.

[0028] In one embodiment, the control section is capable of causing the movable section to be displaced in three or more steps.

[0029] In one embodiment, the control section outputs the control signal being in accordance with a target displacement amount for a point of application of a driving force exerted on the movable section by the driving section among the plurality of driving sections that receives the control signal.

[0030] In one embodiment, the movable section further comprises a light reflecting surface.

13

[0031]   In one embodiment, the apparatus further comprises a light source for generating light.

[0032]   In one embodiment, the apparatus further comprises a wave front information generation section for receiving light which has passed at the light reflecting surface and generating wave front information representing a wave front state of the light, wherein the control section causes the movable section to be displaced in accordance with the wave front information.

EFFECTS OF THE INVENTION

[0033]   According to the present invention, an elastic supporting member supports a movable section at a position intermediate between a plurality of points of application or surrounded by a plurality of points of application. Moreover, a specific relationship is imposed on a spring modulus responsive to a displacement of the movable section along a vertical direction and a spring modulus responsive to a tilt angle of the movable section. As a result, the non-diagonality can be decreased (i.e., diagonality can be

increased) between the driving force of the driving section and the displacement of the movable section, thus easily realizing accuracy improvements and simplification of control of the microactuator. Moreover, a control device for controlling the microactuator can have a simple structure.

[0034] According to the present invention, the non-diagonality between the driving force of the driving section and the displacement of the movable section is small, and the displacements at the respective positions of points of application in the movable section can be independently controlled without mutual interference, whereby simplification of control and high accuracy can be realized.

BRIEF DESCRIPTION OF DRAWINGS

[0035]

[FIG. 1A] An exploded perspective view schematically showing a microactuator according to Embodiment 1 of the present invention.

[FIG. 1B] An exploded perspective view schematically showing an microactuator array according to Embodiment 1 of the

present invention.

[FIG. 2A] An explanatory diagram of an operation of the microactuator according to Embodiment 1 of the present invention.

[FIG. 2B] An explanatory diagram of an operation of the microactuator according to Embodiment 1 of the present invention.

[FIG. 3A] A plan view schematically showing the microactuator according to Embodiment 1 of the present invention.

[FIG. 3B] An explanatory diagram of an operation of the microactuator according to Embodiment 1 of the present invention in a two-dimensional model.

[FIG. 3C] An explanatory diagram of an operation of the microactuator according to Embodiment 1 of the present invention in a two-dimensional model.

[FIG. 4] A plan view schematically showing a microactuator according to Embodiment 1 of the present invention.

[FIG. 5A] A plan view schematically showing a microactuator according to Embodiment 2 of the present invention.

[FIG. 5B] Enlarged views of the neighborhood of a turn-back

portion of an elastic beam of the microactuator according to Embodiment 2 of the present invention.

[FIG. 6A] A plan view schematically showing a microactuator according to Embodiment 3 of the present invention.

[FIG. 6B] A side view schematically showing the microactuator according to Embodiment 3 of the present invention in a state where its elastic supporting member is warped.

[FIG. 7] A diagram schematically showing an apparatus incorporating microactuators according to Embodiment 4 of the present invention.

[FIG. 8A] An explanatory diagram showing a one-dimensional model representing the relationship between coordinate positions of points of application in a movable section according to the Embodiment 4 of the present invention and wave front approximation accuracy.

[FIG. 8B] An explanatory diagram showing a one-dimensional model representing the relationship between coordinate positions of points of application in a movable section according to Embodiment 4 of the present invention and wave front approximation accuracy.

[FIG. 8C] A diagram showing a plotted relationship between the radius of curvature of a phase function according to Embodiment 4 of the present invention and a distance which minimalizes the wave front error.

[FIG. 9A] A plan view schematically showing a microactuator array according to Embodiment 4 of the present invention.

[FIG. 9B] A diagram showing a plotted relationship between the radius of curvature of a phase function according to Embodiment 4 of the present invention and a distance which minimalizes the wave front error.

[FIG. 10] A perspective view schematically showing a conventional microactuator.

[FIG. 11] An explanatory diagram of an operation of a conventional microactuator.

DESCRIPTION OF THE REFERENCE NUMERALS

【0036】

    1   substrate

    4a-4c, 14a-14c, 24a-24c stationary electrodes

    5, 15, 25   elastic supporting member

    5a, 15a, 25a   elastic beam

5h-5j, 15h-15j, 25h-25j   stationary ends

5k-5m, 15k-15m, 25k-25m   movable ends

15n-15s, 25n-25p   turn-back portions

6   movable electrode

6b   mirror section

7   movable section

10, 10a, 10b   microactuator

31   light source

35   microactuator array

42   control section

47   wave front information generation section

BEST MODE FOR CARRYING OUT THE INVENTION

[0037]   Hereinafter, with reference to the figures, embodiments of microactuators according to the present invention and an apparatus incorporating such microactuators will be described.

(Embodiment 1)

[0038]   With reference to FIG. 1A to FIG. 4, a first

embodiment of the microactuator according to the present invention will be described.

[0039]　First, FIG. **1A** will be referred to.　FIG. **1A** is an exploded perspective view schematically showing a microactuator **10** of the present embodiment.

[0040]　The microactuator **10** comprises a base **1**, a movable section **7**, an elastic supporting member **5**, and stationary electrodes **4a**, **4b**, and **4c**.　The microactuator **10** is produced by using an MEMS technique, for example.　The base **1** is a silicon substrate, for example.　On the base **1**, a driving circuit **1a** is provided, with an insulating layer **2** being provided on the driving circuit **1a**.　On the insulating layer **2**, the stationary electrodes **4a** to **4c** and a ground wiring portion **3** are provided.　The movable section **7** is capable of making displacements relative to the base **1**.　The elastic supporting member **5** is elastic, and supports the movable section **7** so as to enable a displacement of the movable section **7** in a direction perpendicular to the plane direction of the base **1**, as well as a tilt of the movable section **7** relative to the base **1**.　Each of the stationary electrodes **4a**

to **4c** functions as a driving section for driving the movable section **7** in a direction perpendicular to the plane direction of the base **1**. As the materials of the stationary electrodes **4a** to **4c** and the ground wiring portion **3**, electrically conductive materials which permit low temperature film formation at 450℃ or less, e.g., an aluminum (Al) alloy or polysilicon germanium (Poly-SiGe), are used. Each of the stationary electrodes **4a** to **4c** is connected to the driving circuit **1a** through a via (not shown) which is formed in the insulating layer **2**. The driving circuit **1a** is able to independently apply a driving voltage in a predetermined voltage range (e.g., 0 to 30V) to each of the stationary electrodes **4a** to **4c**. The driving voltage may be prescribed in multiple steps of values of e.g. 10 bits.

[0041] The elastic supporting member **5** includes three elastic beams **5a** to **5c**, fixture portions **5d** to **5f** for affixing the elastic beams **5a** to **5c** to the base **1**, and a support portion **5g** for supporting the movable section **7**. The elastic beams **5a** to **5c** are connected to the ground wiring portion **3**. Among the end portions of the elastic beams **5a** to

5c, those end portions which are connected to the fixture portions 5d to 5f will be referred to as stationary ends 5h to 5j, whereas those end portions which are connected to the support portion 5g will be referred to as movable ends 5k to 5m.

[0042]   In order to form the elastic supporting member 5, a first sacrificial layer (not shown) may be first formed on the ground wiring portion 3 and the stationary electrodes 4a to 4c by using a photoresist, and then the elastic supporting member 5 may be formed on this first sacrificial layer. As the material of the elastic supporting member 5, an electrically conductive material similar to those of the ground wiring portion 3 and the stationary electrodes 4a to 4c is used.

[0043]   The support portion 5g is connected to a protrusion 6a which is provided in a central portion of the movable electrode 6. The three elastic beams 5a to 5c are linked to one another via the support portion 5g.

[0044]   In order to form the movable section 7, a second sacrificial layer (not shown) may be first formed on the

elastic supporting member 5 by using a photoresist, and then the movable electrode 6 may be formed on the second sacrificial layer. The movable electrode 6 has a generally regular hexagonal shape. As the material of the movable electrode 6, an electrically conductive material similar to those of the ground wiring portion 3 and the stationary electrodes 4a to 4c is used. The upper face of the movable electrode 6 constitutes a mirror section 6b, which is a light reflecting surface. In order to further enhance the light reflection efficiency, gold or a dielectric multilayer film, etc., may be coated on the upper face of the movable electrode 6 to form the mirror section 6b. In the production step of the microactuator 10, the aforementioned first and second sacrificial layers are to be eventually removed with an organic solvent, oxygen plasma or the like, with a gap being left in any removed site. The movable electrode 6 is connected to the driving circuit 1a via the elastic supporting member 5 and the ground wiring portion 3, and is maintained at the ground potential.

[0045]   The movable electrode 6 opposes the three

stationary electrodes 4a to 4c via a gap. When a potential

difference(s) emerges between the movable electrode 6 and the

stationary electrodes 4a to 4c, an electrostatic force(s)

occurs between the movable electrode 6 and the stationary

electrodes 4a to 4c. These electrostatic forces are utilized

as driving forces for driving the movable section 7. When

the movable section 7 is displaced with these driving forces,

the elastic supporting member 5 deforms elastically, and the

posture of the movable section 7 is determined based on the

balance between the elastic restoring force of the elastic

supporting member 5 and the driving forces. By controlling

the size of the driving force generated by each stationary

electrodes 4a to 4c, it becomes possible to control the

amount of displacement of the movable section 7 in a

direction perpendicular to the base 1 and the amount of its

tilt relative to the base 1. If equal driving voltages are

set for the stationary electrodes 4a to 4c, the movable

section 7 will make a vertical displacement in a direction

such that the entire movable section 7 (including the central

portion of the movable section 7) approaches the base 1,

while making hardly any tilt. By making these driving

voltages different from one another, the movable section 7

will tilt in a desired direction. Herein, the tilt relative

to the base 1 is a tilt around two tilt axes which are

parallel to the plane direction of the base 1 and are

perpendicular to each other.

[0046] FIG. 1B shows a microactuator array 35 in which a

plurality of unit cells are arranged, where each unit cell is

a microactuator 10 as described above. FIG. 1B is an

exploded perspective view schematically showing the

microactuator array 35. The movable section 7, the elastic

supporting member 5, and the stationary electrodes 4a to 4c

comprised in the plurality of microactuators 10 are provided

on a single base 1, such that the plurality of microactuators

10 share the single base 1.

[0047] A pitch P between adjoining microactuators 10 is

110 μm, for example. The number of microactuators 10 is 42$\times$

36, for example. The microactuator array 35 comprising such

a plurality of microactuators 10 functions as a micromirror

array.

[0048]   Next, with reference to FIG. 2A to FIG. 3C, the conditions for reducing the non-diagonality between the driving forces generated by the stationary electrodes 4a to 4c and the displacements of the movable section 7 will be described.   The microactuator 10 (FIG. 1A) is supported by the elastic supporting member 5 so as to be capable of bi-axial tilt and mono-axial vertical displacement. Descriptions will be given in the following order: first, a one-dimensional model where mono-axial tilt and mono-axial vertical displacement take place will be described, followed by a description of a two-dimensional model where bi-axial tilt and mono-axial vertical displacement take place.

[0049]   FIG. 2A and FIG. 2B are explanatory diagrams of operations of the microactuator 10 in a one-dimensional model.   FIG. 2A shows a state in which a predetermined voltage is applied only to the stationary electrode 4a to pull the movable electrode 6.

[0050]   A point of application A of a driving force that is exerted by the stationary electrode 4a on the movable electrode 6 of the movable section 7 is a point on an axis

which extends through the center of a region of the stationary electrode **4a** where the driving force occurs and which is perpendicular to the stationary electrode **4a**. A point of application **B** of a driving force that is exerted by the stationary electrode **4b** on the movable electrode **6** of the movable section **7** is a point on an axis which extends through the center of a region of the stationary electrode **4b** where the driving force occurs and which is perpendicular to the stationary electrode **4b**. Since the elastic supporting member **5** supports a generally central portion of the movable electrode **6**, under a one-dimensional model, the elastic supporting member **5** is supporting the movable electrode **6** at a position between the point of application **A** and the point of application **B** (central portion **O**). Around an axis which extends through this central portion **O** and which is perpendicular to the base **1** (FIG. 1A), the stationary electrodes **4a** and **4b** are disposed generally symmetrically. Thus, the distance between the central portion **O** and the point of application **A** and the distance between the central portion **O** and the point of application **B** are both generally L

27

(m). The distance between the point of application **A** and the point of application **B** is 2L.

[0051] It is assumed that a spring modulus for the restoring force which occurs in the elastic supporting member **5** responsive to a vertical displacement δo(m) at the central portion **O** of the movable electrode **6** relative to the base **1** is kz(N/m), and that a spring modulus for the restoration torque which occurs in the elastic supporting member **5** responsive to a tilt angle θ(rad) of the movable electrode **6** relative to the base **1** is kr(Nm/rad). It is assumed that the driving force which occurs at the point of application **A** when a predetermined voltage is applied only to the stationary electrode **4a** to pull the movable electrode **6** is Fa(N), and that the driving force which occurs at the point of application **B** when a predetermined voltage is applied only to the stationary electrode **4b** to pull the movable electrode **6** is Fb(N). It is also assumed that the displacement along the vertical direction of the movable electrode **6** at the point of application **A** is δ(m), and that the displacement along the vertical direction of the movable electrode **6** at the point of

application B is δ'(m). In this case, equilibrium of forces is expressed by (eq. 1).

$$Fa+Fb=(\delta+\delta')/2 \times kz \qquad (eq. 1)$$

[0052] Moreover, equilibrium of moments is expressed by (eq. 2).

$$L \cdot (Fa-Fb)=(\delta-\delta')/2L \times kr \qquad (eq. 2)$$

[0053] Referring to FIG. 2A, in the case where a predetermined voltage is applied only to the stationary electrode 4a to pull the movable electrode 6, a driving force Fa is generated at the point of application A, and the movable electrode 6 is displaced by δ along the vertical direction at the point of application A. In the meantime, at the point of application B where no driving force is generated, the movable electrode 6 is displaced by δ' along the vertical direction. In this case, since Fb=0, it follows from (eq. 1) and (eq. 2) that:

$$Fa=(\delta+\delta')/2 \times kz; \text{ and } \qquad (eq. 3)$$

$$L \cdot Fa=(\delta-\delta')/2L \times kr. \qquad (eq. 4)$$

From (eq. 3) and (eq. 4), it follows that:

$$\delta=(1/kz+L^2/kr)Fa; \text{ and } \qquad (eq. 5)$$

$\delta' = (1/kz - L^2/kr)Fa.$ (eq. 6)

Therefore, the degree of non-diagonality δ'/δ is given by (eq. 7).

【0054】

$$\frac{\delta'}{\delta} = \frac{1 - (L^2 \cdot kz / kr)}{1 + (L^2 \cdot kz / kr)}$$ (eq. 7)

【0055】 From (eq. 7), it is known that by approximating the value of $L^2 \cdot kz/kr$ to one, the degree of non-diagonality δ'/δ can be reduced to a desired value. There exists a direct correspondence between the degree of non-diagonality δ'/δ and the value of $L^2 \cdot kz/kr$, and this relationship is expressed in (Table 1).

【0056】   [Table 1]

Degree of non-diagonality δ'/δ	Necessary condition for $L^2 \cdot kz/kr$
0.5	$0.33 \leqq L^2 \cdot kz/kr \leqq 3$
0.33... (=1/3)	$0.5 \leqq L^2 \cdot kz/kr \leqq 2$
0.25	$0.6 \leqq L^2 \cdot kz/kr \leqq 1.67$
0.2	$0.67 \leqq L^2 \cdot kz/kr \leqq 1.5$
0.1	$0.82 \leqq L^2 \cdot kz/kr \leqq 1.2$

【0057】 It has already been described that it is very

difficult to reduce the degree of non-diagonality δ'/δ to 1/3 or less in a structure where the elastic supporting member supports the movable electrode at the outer periphery, as in the conventional microactuator **1000** (FIG. **10**). On the other hand, the microactuator **10** of the present invention has a structure such that the elastic supporting member **5** supports the generally central portion **O** of the movable section **7**, and, by further imposing on the spring moduli kz and kr and the distance L the relationship of:

$$0.5 \leqq L^2 \cdot kz/kr \leqq 2,$$

the degree of non-diagonality δ'/δ can be reduced to 1/3 or less. By thus reducing the non-diagonality, accuracy improvements and simplification of control of the microactuator **10** can be easily realized. Moreover, the control device for controlling the microactuator can have a simple structure.

[0058] Note that it is more desirable if the degree of non-diagonality δ'/δ is 1/10 or less. From (Table 1), by imposing on the spring moduli kz and kr and the distance L the relationship of:

31

$$0.82 \leq L^2 \cdot kz/kr \leq 1.2,$$

it becomes possible to reduce the degree of non-diagonality δ'/δ to 1/10 or less.

[0059]   Although a case has been described where only the stationary electrode **4a** generates a driving force, the above relationships can also be true in the case where each of the stationary electrodes **4a** and **4b** generates an arbitrary driving force. This will be described with reference to FIG. **2B**. FIG. **2B** shows a state in which independent voltages are applied to the stationary electrodes **4a** and **4b** to pull the movable electrode **6**.

[0060]   It is assumed that the driving force generated by the stationary electrode **4a** is Fa(N), and that the driving force generated by the stationary electrode **4b** is Fb(N). Moreover, it is assumed that displacement along the vertical direction of the movable electrode **6** at the point of application **A** is δa(m), and that the displacement along the vertical direction of the movable electrode **6** at the point of application **B** is δb(m). In this case, when Fb=0, it follows from (eq. 1) and (eq. 2) that:

$\delta a=(1/kz+L^2/kr)Fa;$ and   (eq. 8)

$\delta b=(1/kz-L^2/kr)Fa.$ (eq. 9)

When Fa=0, it follows from (eq. 1) and (eq. 2) that:

$\delta a=(1/kz-L^2/kr)Fb;$ and   (eq. 10)

$\delta b=(1/kz+L^2/kr)Fb.$ (eq. 11)

From (eq. 8) to (eq. 11), the relationship between the displacements δa and δb and the driving forces Fa and Fb is given by (eq. 12).

[0061]

$$
\begin{bmatrix} \delta a \\ \delta b \end{bmatrix} = \begin{bmatrix} \dfrac{1}{kz} + \dfrac{L^2}{kr} \end{bmatrix} \begin{bmatrix} 1 & \dfrac{1-(L^2 \cdot kz/kr)}{1+(L^2 \cdot kz/kr)} \\ \dfrac{1-(L^2 \cdot kz/kr)}{1+(L^2 \cdot kz/kr)} & 1 \end{bmatrix} \begin{bmatrix} Fa \\ Fb \end{bmatrix}
$$

(eq. 12)

[0062] In the matrix at the right-hand side of (eq. 12), the value of the ratio between the non-diagonal component and the diagonal component coincides with the degree of non-diagonality as has been described with reference to (eq. 7). From this, by imposing on the spring moduli kz and kr and the distance L the relationship of:

$0.5 \leqq L^2 \cdot kz/kr \leqq 2,$

it becomes possible to reduce the displacement interferences at the points of application **A** and **B** when arbitrary driving forces are generated by the stationary electrodes **4a** and **4b** (i.e., the interference of the driving force generated by the stationary electrode **4a** with the displacement of the point of application **B**, and the interference of the driving force generated by the stationary electrode **4b** with the displacement of the point of application **A**) to 1/3 or less, and enhance the independent controllability of displacements at the points of application **A** and **B**.

[0063]   Moreover, if $L^2 \cdot kz/kr$ further satisfies the condition of:

$$1 \leqq L^2 \cdot kz/kr,$$

then the non-diagonal terms in (eq. 12) will take negative values.   This condition will facilitate the correction of displacements associated with non-diagonality in a structure where driving forces Fa and Fb only produce pulling forces, as in the case where electrostatic forces are employed as driving forces.

[0064]   The reason for this will be described again

referring to FIG. 2A.

[0065]   In the case where the condition of:

$$1 \leqq L^2 \cdot kz/kr$$

is satisfied, when one end of the movable electrode **6** at the point of application **A** side is displaced in a direction of approaching the base **1** due to the driving force Fa which is generated by driving the stationary electrode **4a**, another end of the movable electrode **6** at the point of application **B** side will be displaced in a direction of becoming more distant from the base **1**, and the displacement δ' at the point of application **B** due to non-diagonality will take a negative value.   In order to correct this displacement, a pulling force may be generated by the stationary electrode **4b**.   In the case where the displacement δ' due to non-diagonality is generated in a direction of approaching the stationary electrode **4b**, it would be very difficult to correct this displacement in a structure where only pulling force, e.g., electrostatic force, is generated.   However, even in a structure where only pulling force is generated, if the displacement δ' due to non-diagonality occurs in a direction

of becoming more distant from the stationary electrode **4b**, correction of displacements associated with non-diagonality can be easily performed, basically by appropriately setting the sizes of the driving forces Fa and Fb. As a result, any control device which performs the correction of displacements associated with non-diagonality can have a simple structure.

[0066] Next, with reference to FIG. **3A** to FIG. **3C**, a two-dimensional model where bi-axial tilt and mono-axial vertical displacement take place will be described. FIG. **3A** to FIG. **3C** are explanatory diagrams of operations of the microactuator **10** under a two-dimensional model.

[0067] FIG. **3A** is a plan view schematically the microactuator **10**, where an x axis and a y axis, whose origin is at the central portion **O** of the movable electrode **6**, are set as shown in FIG. **3A**.

[0068] A point of application **A** of a driving force Fa that is exerted by the stationary electrode **4a** on the movable electrode **6** of the movable section **7** is a point on an axis which extends through the center of a region of the stationary electrode **4a** where the driving force Fa occurs and

which is perpendicular to the stationary electrode **4a**. A

point of application **B** of a driving force Fb that is exerted

by the stationary electrode **4b** on the movable electrode **6** is

a point on an axis which extends through the center of a

region of the stationary electrode **4b** where the driving force

Fb occurs and which is perpendicular to the stationary

electrode **4b**. A point of application **C** of a driving force Fc

that is exerted by the stationary electrode **4c** on the movable

electrode **6** is a point on an axis which extends through the

center of a region of the stationary electrode **4c** where the

driving force Fc occurs and which is perpendicular to the

stationary electrode **4c**. The elastic supporting member **5**

supports the movable electrode **6** at a position surrounded by

the points of application **A**, **B**, and **C** (which in the present

embodiment is a generally central portion of the movable

electrode **6**). In a linear approximation where the stationary

electrode **4a** and the movable electrode **6** are regarded as

constituting parallel-plate electrodes, the point of

application **A** is located at the center of a region of the

movable electrode **6** that overlaps the stationary electrode

4a. The same is also true of the points of application **B** and **C**. Around the central portion **O** at which the elastic supporting member **5** supports the movable electrode **6**, the stationary electrodes **4a** to **4c** are disposed so as to be rotation symmetrical. The distance of each of the points of application **A** to **C** from the central portion **O** is R(m). The points of application **A** to **C** are positioned on the circumference of a circle which has the radius R and is centered around the central portion **O**, and are positioned with equal angle intervals of 120° as viewed from the central portion **O**.

[0069] FIG. 3B is a schematic diagram of a cross section of the microactuator **10** along the y axis, and FIG. 3C is a schematic diagram of a cross section of the microactuator along the x axis. It is assumed that the stationary electrodes **4a**, **4b**, and **4c** independently generate driving forces Fa, Fb, and Fc, whereby the movable electrode **6** is displaced, in a direction perpendicular to the base **1**, by δ a, δ b, and δ c at the points of application **A**, **B**, and **C**, respectively.

[0070]　It is assumed that a spring modulus for the restoring force which occurs in the elastic supporting member 5 responsive to a vertical displacement δo(m) of the movable electrode **6** relative to the base **1** is kz(N/m); a spring modulus for the restoration torque which occurs in the elastic supporting member **5** responsive to a tilt angle θ x(rad) of a tilting of the movable electrode **6** around the x axis is krx(Nm/rad); and a spring modulus for the restoration torque which occurs in the elastic supporting member **5** responsive to a tilt angle θ y(rad) of a tilting of the movable electrode **6** around the y axis is kry(Nm/rad).

[0071]　The relationship between the displacements δ a, δ b, and δ c and the driving forces Fa, Fb, and Fc is given by (eq. 13).

[0072]

$$
\begin{pmatrix} \delta a \\ \delta b \\ \delta c \end{pmatrix} = \begin{pmatrix} \dfrac{1}{kz}+\dfrac{R^2}{krx} & \dfrac{1}{kz}-\dfrac{R^2}{2krx} & \dfrac{1}{kz}-\dfrac{R^2}{2krx} \\[2ex] \dfrac{1}{kz}-\dfrac{R^2}{2krx} & \dfrac{1}{kz}+\dfrac{R^2}{4krx}+\dfrac{3R^2}{4kry} & \dfrac{1}{kz}+\dfrac{R^2}{4krx}-\dfrac{3R^2}{4kry} \\[2ex] \dfrac{1}{kz}-\dfrac{R^2}{2krx} & \dfrac{1}{kz}+\dfrac{R^2}{4krx}-\dfrac{3R^2}{4kry} & \dfrac{1}{kz}+\dfrac{R^2}{4krx}+\dfrac{3R^2}{4kry} \end{pmatrix} \begin{pmatrix} Fa \\ Fb \\ Fc \end{pmatrix}
$$

(eq. 13)

[0073] In (eq. 13), by approximating the value of $R^2 \cdot$ kz/krx to two and approximating the value of krx to the value of kry, it becomes possible to reduce all non-diagonal components to a desired value. From this, by allowing the elastic supporting member **5** to support the central portion **O** of the movable electrode **6**, and imposing a specific relationship on R, kz, krx, and kry, it becomes possible to reduce the displacement interferences at the points of application **A** to **C** when arbitrary driving forces are generated by the stationary electrodes **4a** to **4c** to a predetermined value or less, and enhance the independent controllability of displacements at the points of application **A** to **C**.

[0074] Examples of conditions for R, kz, krx, and kry that are necessary for reducing the non-diagonality are shown in (Table 2).

【0075】 [Table 2]

Degree of non-diagonality	Example conditions for R, kz, krx, kry
0.33... (=1/3)	$1 \leqq R^2 \cdot kz/krx \leqq 5$ $1 \leqq R^2 \cdot kz/kry \leqq 5$ $0.67 \leqq krx/kry \leqq 1.5$
0.25	$1.1 \leqq R^2 \cdot kz/krx \leqq 4$ $1.1 \leqq R^2 \cdot kz/kry \leqq 4$ $0.71 \leqq krx/kry \leqq 1.4$
0.2	$1.3 \leqq R^2 \cdot kz/krx \leqq 3.3$ $1.3 \leqq R^2 \cdot kz/kry \leqq 3.3$ $0.77 \leqq krx/kry \leqq 1.3$
0.1	$1.6 \leqq R^2 \cdot kz/krx \leqq 2.5$ $1.6 \leqq R^2 \cdot kz/kry \leqq 2.5$ $0.87 \leqq krx/kry \leqq 1.15$

【0076】 By the elastic supporting member **5** supporting the generally central portion **O** of the movable electrode **6**, and by imposing on the spring moduli kz, krx, and kry and the distance **R** the relationships of:

$1 \leqq R^2 \cdot kz/krx \leqq 5$;

$1 \leqq R^2 \cdot kz/kry \leqq 5$; and

$0.67 \leqq krx/kry \leqq 1.5$,

it becomes possible to reduce the degree of non-diagonality to 1/3 or less in a microactuator **10** having freedom along three axes including mono-axial vertical displacement and bi-axial tilt.

[0077] Note that it is more desirable if the degree of non-diagonality is 1/10 or less. From (Table 2), by imposing on the spring moduli kz, krx, and kry and the distance R the relationships of:

$1.6 \leqq R^2 \cdot kz/krx \leqq 2.5$;

$1.6 \leqq R^2 \cdot kz/kry \leqq 2.5$; and

$0.87 \leqq krx/kry \leqq 1.15$,

it becomes possible to reduce the degree of non-diagonality δ'/δ to 1/10 or less.

[0078] Moreover, if the $R^2 \cdot kz/kr$ further satisfies the conditions of:

$2 \leqq R^2 \cdot kz/krx$; and

$2 \leqq R^2 \cdot kz/kry$,

it becomes possible to facilitate the correction of displacements associated with non-diagonality even in the

case where only pulling forces are generated as driving forces Fa to Fc, as has been described with respect to a one-dimensional model.

[0079]   Next, with reference to FIG. 4, specific dimension values for the microactuator 10 for satisfying the aforementioned conditions will be described. FIG. 4 is a plan view schematically showing the microactuator 10.

[0080]   The central portion O, the points of application A to C, and the distance R have been described with respect to FIG. 3A, and the descriptions thereof are omitted here. The distance R in the microactuator 10 shown in FIG. 4 is 37μm. A distance H_1 from the central portion O to the movable end 5k of the elastic supporting member 5 is 5.5μm; a distance H_2 from the central portion O to the stationary end 5h of the elastic supporting member 5 is 45.5μ m; and a distance H_3 from the central portion O to the center of the fixture portion 5d of the elastic supporting member 5 is 51μm. The support portion 5g has a width W_1 of 11μm; the elastic beam 5a has a width W_2 of 4μm; and the fixture portion 5d has a width W_3 of 11μ m. The thickness of the elastic supporting

member **5** is preferably in the range from 0.1 to 1μm, and is 0.5μm herein. In the case where the material of the elastic supporting member **5** is an aluminum alloy (e.g., aluminum silicon), the Young's modulus is 69GPa and the Poisson's ratio is 0.35.

[0081] The stationary end **5h**, which is the end that is connected to the base **1**, is located more to the outside than is the movable end **5k**, which is the end that is connected to the movable electrode **6**, and the distance between the stationary end **5h** and the central portion **O** is longer than the distance between the movable end **5k** and the central portion **O**. Along the elastic beam **5a** extending from the stationary end **5h** to the movable end **5k**, the linear distance between the two farthermost points thereof is defined as **H**. Herein, the distance **H** is equal to the length of the elastic beam **5a**, and is 40μm. Since the values of kr/krx and kr/kry are approximately in inverse proportion with the distance **H** raised to the second power, it is possible to obtain desired values of kz/krx and kr/kry by appropriately adjusting the value of the distance **H**. It is preferable to determine the

relationship between the distance **H** and the distance **R** so as to satisfy:

0.8 ≦ H/R ≦ 1.6.

Under the aforementioned values of **H** and **R** (H=40 μ m, R=37μm), the value of H/R is 1.08, thus satisfying the relationship of:

0.8 ≦ H/R ≦ 1.6.

【0082】 An elastic supporting member **5** having the aforementioned values exhibited characteristics such that: kz=1.16(N/m), krx=7.29×10^{-10}(Nm/rad), and kry=7.90×10^{-10}(Nm/rad). Herein, the values of $R^2 \cdot$kz/krx, $R^2 \cdot$kz/kry, and krx/kry are 2.18, 2.02, and 1.08, respectively, thus satisfying the conditions of:

1 ≦ $R^2 \cdot$kz/krx ≦ 5;

1 ≦ $R^2 \cdot$kz/kry ≦ 5; and

0.67 ≦ krx/kry ≦ 1.5.

Through calculations based on (eq. 13), it can be seen that the non-diagonality would be 3% or less under these conditions. Thus, according to the present invention, it is possible to realize a microactuator having a very small non-

diagonality.

[0083]   Note that each side of the movable electrode **6** has

a length **Q** of 62μm, ensuring that the stationary electrodes

4a to **4c** and the elastic supporting member **5** are all disposed

under the plane region of the movable electrode **6**.

[0084]   Now, it will be described how the condition:

$0.5 \leqq L^2 \cdot kz/kr \leqq 2$,

which has been described by using a one-dimensional model, is

also applicable to a two-dimensional model.

[0085]   When one pays attention to the two stationary

electrodes **4a** and **4b**, the stationary electrodes **4a** and **4b** are

in such a planar positioning that they are allocated to

opposite sides of a tilt axis **U** (FIG. 4) which extends

through the central portion **O**.   The restoration torque kr

with respect to the tilt axis **U** is equal to krx, and the

distance **L** between each of the points of application **A** and **B**

and the tilt axis **U** is equal to $\sqrt{3}R/2$.   In this case, $L^2 \cdot$

kz/kr is 1.58, thus satisfying the condition of:

$0.5 \leqq L^2 \cdot kz/kr \leqq 2$.

[0086]   As   described   above,   according   to   the   present

embodiment, by allowing the central portion O of the movable

electrode 6 of the movable section 7 to be supported by the

elastic supporting member 5, and imposing a specific

relationship between the spring moduli responsive to vertical

displacements and tilt angles of the movable section 7, it

becomes possible to reduce the non-diagonality between

driving force and displacement.

[0087]   In the present embodiment, the movable section 7

includes movable electrodes 6, such that the stationary

electrodes 4a to 4c which form pairs of parallel-plate

electrodes with the movable electrode 6 function as driving

sections for driving the movable section 7.   However, the

present invention is not limited thereto.   The driving

sections may be any elements that generate driving forces for

the movable section in a direction perpendicular to the base

1.   For example, the stationary electrodes 4a to 4c and the

movable electrode 6 may constitute pairs of vertical comb-

like electrodes.   Moreover, the driving sections may be any

elements that generate driving forces other than

electrostatic forces, e.g., electromagnetic forces other than

electrostatic forces. Such driving forces are preferably non-contact forces, but they may also be contact forces as long as they do not introduce a large disturbance in the specific relationship between the spring moduli kz, kr, krx, and kry and the distances **L** and **R**.

[0088] The microactuator **10** of the present embodiment is capable of bi-axial tilt and mono-axial vertical displacement. However, as is clear from the description of the principles in a one-dimensional model, it will be appreciated that the present invention is also applicable to a microactuator which is capable of mono-axial tilt and mono-axial vertical displacement.

[0089] Although the microactuator **10** of the present embodiment has a planar shape in which the respective constituent elements are disposed symmetrically around the central portion **O**, the present invention is not limited thereto. According to the present invention, it is possible to obtain the effect of reducing non-diagonality even in a structure in which the constituent elements are not in symmetric arrangement.

(Embodiment 2)

[0090]   With reference to FIG. 5A and FIG. 5B, a second embodiment of the microactuator according to the present invention will be described.

[0091]   First, FIG. 5A will be referred to. FIG. 5A is a plan view schematically showing a microactuator 10a of the present embodiment.

[0092]   The microactuator 10a comprises an elastic supporting member 15 instead of the elastic supporting member 5 of the microactuator 10 of Embodiment 1, and comprises stationary electrodes 14a to 14c instead of the stationary electrodes 4a to 4c. The planar shape of the elastic supporting member 15 is a meander shape, such that elastic beams 15a to 15c of the elastic supporting member 15 have turn-back portions 15n to 15s where the direction in which each beam extends is reversed by about 180°.

[0093]   The stationary electrodes 14a to 14c have a smaller area than do the stationary electrodes 4a to 4c, this being in order to allow for occupancy by the elastic supporting member 15. As a result of this, the points of application A

to **C** are located farther away from the central portion **O** (R=39μm).

[0094]   The elastic supporting member **15** includes three elastic beams **15a** to **15c**, fixture portions **15d** to **15f** for affixing these elastic beams **15a** to **15c** to a base **1** (FIG. **1A**), and a support portion **15g** for supporting a movable section **7** (FIG. **1A**).   Among the end portions of the elastic beams **15a** to **15c**, those end portions which are connected to the fixture portions **15d** to **15f** will be referred to as stationary ends **15h** to **15j**, whereas those end portions which are connected to the support portion **15g** will be referred to as movable ends **15k** to **15m**.

[0095]   Herein, the planar shape of the elastic supporting member **15** will be described by paying attention to the elastic beam **15a**.   The elastic beam **15a** has a meander shape, and includes two turn-back portions **15n** and **15o** where the direction in which each beam extends is turned back by about 180°.   By assigning a meander shape to the elastic beam **15a**, the substantial beam length is elongated and the spring moduli kz, krx, and kry are reduced, thus making it possible

to obtain a large displacement with low voltage driving.

[0096]   Herein, a distance H_1 from the central portion O to the movable end 15k is 5.5μm; a distance H_2 from the central portion O to the stationary end 15h is 51.5 μm; and a distance H_3 from the central portion O to the center of the fixture portion 15d is 57μm. Moreover, the support portion 15g has an effective width W_1 of 13μm; the elastic beam 15a has a width W_2 of 3 μm; and the fixture portion 15d has a width W_3 of 11μm. The thickness of the elastic supporting member 15 is preferably in the range from 0.1 to 1μm, and is 0.5μm herein. In the case where the material of the elastic supporting member 15 is an aluminum alloy, the Young's modulus is 69GPa and the Poisson's ratio is 0.35.

[0097]   Along the elastic beam 15a, the distance H between the two farthermost points thereof is equal to the linear distance between the stationary end 15h and the movable end 15k, and is 46 μm. In the case where H and R have these values (H=46 μm, R=39 μm), the value of H/R is 1.18, thus satisfying the relationship of:

$0.8 \leqq H/R \leqq 1.6$.

[0098]   The beam overall length of the elastic beam **15a** is

120μm, which is 2.61 times as large as the distance **H**.

[0099]   The fixture portions **15d** to **15f** may be formed

integrally with the fixture portions of any adjoining

microactuator.   The support portion **15g** is connected with the

movable electrode **6** at three sites which are shown hatched in

FIG. **5A**.   The reason for employing three connection sites is

in order to further enhance the connection strength between

the movable electrode **6** and the elastic supporting member **15**.

The positions of the connection sites may be anywhere on the

generally central portion **O**.   Each side of the movable

electrode **6** has a length **Q** of 62μm.

[0100]   An elastic supporting member **15** having the

aforementioned values exhibited characteristics such that:

$kz=0.34$(N/m), $krx=2.34\times10^{-10}$(Nm/rad),   and $kry=2.57\times10^{-10}$(Nm/rad).   Herein, the values of $R^2\cdot kz/krx$, $R^2\cdot kz/kry$, and

krx/kry   are   2.19,   2.00,   and   1.10,   respectively,   thus

satisfying the conditions of:

$$1 \leqq R^2\cdot kz/krx \leqq 5;$$

$$1 \leqq R^2\cdot kz/kry \leqq 5; \text{ and}$$

$$0.67 \leqq krx/kry \leqq 1.5.$$

【0101】 The effects obtained from assigning meander shapes to the elastic beams **15a** to **15c** will be described in comparison with the case where the elastic beams have linear shapes.

【0102】 In the case where the elastic beams have linear shapes, if the length of each beam is increased to n times as much in order to reduce the spring modulus of the elastic beam, then the spring modulus kr (or krx, kry) concerning the tilt angle becomes approximately 1/n, so that the spring modulus kz concerning vertical displacement becomes approximately $1/n^3$. Thus, kz/kr, which is a value of the ratio between kr and kz, becomes approximately $1/n^2$. In other words, the value of kz/kr rapidly decreases with an increase in n, and therefore it is difficult to satisfy the conditions of:

$$0.5 \leqq L^2 \cdot kz/kr \leqq 2, \text{ or}$$

$$1 \leqq R^2 \cdot kz/krx \leqq 5; \text{ and}$$

$$1 \leqq R^2 \cdot kz/kry \leqq 5.$$

【0103】 On the other hand, in the case where the elastic

beams have meander shapes, it is possible to increase the substantial beam overall length to n times as much by turning back the beams a plurality of times, while substantially maintaining the length of the distance **H** so as to condition:

$0.8 \leqq H/R \leqq 1.6$.

In this case, the spring modulus kr (or krx, kry) concerning the tilt angle becomes approximately 1/n, and the spring modulus kz concerning vertical displacement also becomes approximately 1/n. Therefore, the value of the ratio kz/kr between kr and kz becomes substantially constant, with hardly any dependence on n. Therefore, in the case where the elastic beams have meander shapes, it is possible to reduce the spring modulus merely by increasing the number of turn-backs in each beam, while satisfying the conditions of:

$0.5 \leqq L^2 \cdot kz/kr \leqq 2$, or

$1 \leqq R^2 \cdot kz/krx \leqq 5$; and

$1 \leqq R^2 \cdot kz/kry \leqq 5$.

[0104] The reason why, in the case where the elastic beams have meander shapes, the spring modulus kz concerning vertical displacement changes in proportion with 1/n, as

opposed to $1/n^3$, will be described with reference to FIG. 5B.

[0105]   FIG. 5B is enlarged views of the neighborhood of the turn-back portion 15o of the elastic beam 15a. The upper view is a plan view of the turn-back portion 15o, whereas the lower view is a side view of the turn-back portion 15o.

[0106]   Assuming that the elastic beam 15a has a flex angle of ψ at the turn-back portion 15o, the amount of change $\Delta\varepsilon(S_1 \to S_2)$ in vertical displacement, responsive to a minute displacement Δx from points S_1 to S_2, is $\psi\Delta x$.

[0107]   When an amount of change $\Delta\varepsilon(S_3 \to S_4)$ in vertical displacement responsive to a minute displacement $(-\Delta x)$ from points S_3 to S_4 is considered, there exists a term $(-\psi\Delta x)$. Therefore, when a vertical displacement from points S_1 to S_4 is considered, the ψ terms are cancelled so that higher-order terms $\Delta\psi\Delta x$ are left.

[0108]   Thus, since the direction in which the elastic beam extends is reversed at a turn-back portion, a portion of the vertical displacement associated with a flex angle component of the elastic beam is partially cancelled to become smaller. As a result, the characteristics of the spring modulus kz can

be brought closer to $1/n$ than $1/n^3$.

[0109]   As described above, according to the present

embodiment, since the elastic supporting member **15** has turn-

back portions **15n** to **15s** where the direction in which each

beam extends is reversed, the rigidity of the beams can be

decreased while hardly changing the value of the ratio

between the spring modulus kz and the spring modulus kr. As

a result, the effect of reducing non-diagonality and the

effect of obtaining a large displacement of the movable

section **7** with low voltage driving can both be obtained.

(Embodiment 3)

[0110]   With reference to FIG. **6A** and FIG. **6B**, a third

embodiment of the microactuator according to the present

invention will be described.

[0111]   First, FIG. **6A** will be referred to.   FIG. **6A** is a

plan view schematically showing a microactuator **10b** of the

present embodiment.

[0112]   The   microactuator   **10b**   comprises   an   elastic

supporting member **25** instead of the elastic supporting member

15 of the microactuator 10a of Embodiment 2, and comprises stationary electrodes 24a to 24c instead of the stationary electrodes 14a to 14c. Stationary ends 25h to 25j of the elastic supporting member 25 are disposed in positions which are closer to the central portion O than are turn-back portions 25n to 25p.

[0113] The stationary electrodes 24a to 24c are disposed in positions such that a distance R between points of application A to C and the central portion O is $38.5\,\mu$m.

[0114] The elastic supporting member 25 includes three elastic beams 25a to 25c, fixture portions 25d to 25f for affixing these elastic beams 25a to 25c to a base 1 (FIG. 1A), and a support portion 25g for supporting a movable section 7 (FIG. 1A). Among the end portions of the elastic beams 25a to 25c, those end portions which are connected to the fixture portions 25d to 25f will be referred to as stationary ends 25h to 25j, whereas those end portions which are connected to the support portion 25g will be referred to as movable ends 25k to 25m.

[0115] Herein, the planar shape of the elastic supporting

member 25 will be described by paying attention to the elastic beam 25a. The elastic beam 25a has a meander shape, and includes an odd number (which herein is one) of turn-back portions 25n where the direction in which each beam extends is turned back by about 180°. The distance between the turn-back portion 25n and the central portion O is longer than the distance between the fixture portion 25d and the central portion O.

[0116] Herein, a distance H_1 from the central portion O to the movable end 25k is 6 μm; a distance H_2 from the central portion O to the stationary end 25h is 17.5 μm; and a distance H_3 from the central portion O to the center of the fixture portion 25d is 10 μm. Moreover, the support portion 25g has an effective width W_1 of 9 μm, and the elastic beam 25a has a width W_2 of 3 μm. The thickness of the elastic supporting member 25 is preferably in the range from 0.1 to 1 μm, and is 0.5 μm herein. In the case where the material of the elastic supporting member 25 is an aluminum alloy, the Young's modulus is 69GPa and the Poisson's ratio is 0.35.

[0117] Along the elastic beam 25a, the distance H between

58

the two farthermost points thereof is 41.5 μ m, which corresponds to the distance between the movable end **25k** and the turned portion **25n** in the present embodiment. In the case where **H** and **R** have these values (H=41.5μm, R=38.5μm), the value of H/R is 1.08, thus satisfying the relationship of:

$$0.8 \leq H/R \leq 1.6.$$

[0118] The beam overall length of the elastic beam **25a** is 74.5μm, which is 1.8 times as large as the distance **H**.

[0119] An elastic supporting member **25** having the aforementioned values exhibited characteristics such that: kz=0.55(N/m), krx=3.70×10^{-10}(Nm/rad), and kry=4.08×10^{-10}(Nm/rad). Herein, the values of $R^2 \cdot$kz/krx, $R^2 \cdot$kz/kry, and krx/kry are 2.20, 2.00, 1.10, respectively, thus satisfying the conditions of:

$$1 \leq R^2 \cdot kz/krx \leq 5;$$

$$1 \leq R^2 \cdot kz/kry \leq 5; \text{ and}$$

$$0.67 \leq krx/kry \leq 1.5.$$

[0120] Referred to FIG. **6B**, the effects obtained by disposing the stationary ends **25h** to **25j** of the elastic

supporting member **25** in positions which are closer to the central portion **O** than are the turn-back portions **25n** to **25p** will be described.

[0121]   FIG. **6B** is a side view schematically showing a state in which the elastic supporting member **25** is warped.

[0122]   The elastic supporting member **25** may have warpage due to a residual stress gradient or the like which occurs during the film formation process, for example. Due to the influence of such warpage, a height error Δz along the vertical direction may occur between the support portion **25g** and the fixture portion **25d**. Assuming that the warpage has a radius of curvature of ρ, Δz is expressed as, by approximation:

$$\Delta z = H_3^2 / (2\rho).$$

[0123]   Therefore, the more the distance H_3 from the central portion **O** to the center of the fixture portion **25d** is reduced, the more the height error Δz can be reduced, in proportion with the distance H_3 raised to the second power. By disposing the stationary ends **25h** to **25j** to positions which are closer to the central portion **O** than are the turn-

back portions 25n to 25p, the distance H_3 can be reduced.

[0124]   As described above, according to the present embodiment, the stationary ends 25h to 25j of the elastic supporting member 25 are disposed in positions which are closer to the central portion O than are the turn-back portions 25n to 25p. As a result, even if warpage occurs in the elastic supporting member 25 due to a residual stress gradient or the like which occurs during the film formation process, for example, the height error Δz of the movable electrode 6 along the vertical direction can be kept small. It will also be appreciated that the effect of reducing non-diagonality and the effect of obtaining a large displacement of the movable section 7 with low voltage driving as described in Embodiment 2 are also obtained.

(Embodiment 4)

[0125]   With reference to FIG. 7 to FIG. 9B, an embodiment of an apparatus which comprises microactuators according to the present invention will be described.

[0126]   First, FIG. 7 will be referred to. FIG. 7 is a

diagram schematically showing an apparatus **30** comprising microactuators according to the present embodiment. An apparatus comprising microactuators according to the present invention may be, for example, an optical pickup or an optical disk apparatus which performs recording/reproduction of information for an optical disk, but is not limited thereto. As an example of an apparatus comprising the microactuator according to the present invention, the apparatus **30**, which is an optical disk apparatus, will be described.

[0127] The apparatus **30** comprises a light source **31**, a collimator lens **32**, a polarization beam splitter **33**, a 1/4 wavelength plate **34**, a microactuator array **35**, an objective lens **36**, an objective lens actuator **38**, a wave front information generation section **47**, and a control section **42**.

[0128] As has been described with reference to FIG. **1B**, the microactuator array **35** includes a plurality of microactuators **10**. Note that the microactuator array **35** may comprise a plurality of microactuators **10a** or **10b** instead of the microactuators **10**, or comprise a combination of the

microactuators **10**, **10a**, and **10b**.

[0129]   The control section **42** outputs control signals to the stationary electrodes **4a** to **4c** as driving voltages, thus controlling the displacement (vertical displacement and tilt) of the movable section **7**.   The control section **42** causes the movable section **7** to be displaced to a desired posture, thus modulating the wave front of light which enters the mirror section **6b**.

[0130]   Next, the operation of the apparatus **30** will be described in more detail.

[0131]   The light source **31** is a GaN laser device, for example.   A light beam which is emitted from the light source **31** is converted by the collimator lens **32** into a light beam of an infinite system, and enters the polarization beam splitter **33**.   In this light beam, only the P-polarized light component is transmitted through the polarization beam splitter **33**, whereas the remaining S-polarized light component is reflected so as to enter a front light monitor (not shown).   The transmitted P-polarized light component is converted by the 1/4 wavelength plate **34** into circularly

polarized light.

[0132]   On   the   microactuator   array   **35**,   a   plurality   of
microactuators **10** are arranged in a two-dimensional array.
Each movable section **7** includes a mirror section **6b** which is
a light reflecting surface, and reflects a light beam.   The
movable section **7** is displaced in accordance with the sizes
of the voltages applied to the stationary electrodes **4a** to
4c, and causes local changes in the wave front of the light
beam.   The incident angle and the outgoing angle of light
with   respect   to   the   microactuator   array   **35**   are   each
prescribed to be 45°.

[0133]   The light beam whose wave front has been changed by
the microactuator array **35** is converged by the objective lens
36 onto a recording layer of the disk **37**.   The objective lens
actuator   **38**   translates   the   objective   lens   **36**   in   two
directions, i.e., an optical axis direction of the light beam
and a direction perpendicular to the optical axis, so as to
realize focusing of the light beam onto a desired recording
layer, as well as tracking along a desired recording track.

[0134]   The disk **37** is an optical storage medium having a

plurality of recording layers that are disposed at predetermined intervals, and a substrate portion which covers the recording layer for protection and which is capable of transmitting light. In order to prevent loss of aberration information concerning odd symmetric aberrations in the forth and return paths, it would be more preferable to allow the recording layer to have diffusing properties or fluorescence. The light beam which has been reflected at the recording layer of the disk 37 again passes through the mirror sections 6b of the microactuator array 35 and the 1/4 wavelength plate 34. Since most of this light beam is an S-polarized light component, it is reflected by the polarization beam splitter 33, and enters the wave front information generation section 47. The wave front information generation section 47 generates wave front information indicating the wave front state of the light beam. The wave front information generation section 47 includes a hologram 39, a lens 40, and a photodetector 41. Although the wave front information generation section 47 is herein illustrated as being a modal-type wave front sensor, it may also be a Shack-Hartmann type

wave front sensor, or any other aberration detection method may be used, e.g., that which is described in Japanese Laid-Open Patent Publication No. 2000-155979. A modal-type wave front sensor is disclosed in the following publication.

[0135] M.A.A.Neil, M.J.Booth, and T.Wilson, "New modal wave-front sensor: a theoretical analysis," J. Opt. Soc. Am. A / Vol. 17, No. 6, pp. 1098 - 1107 (2000)

[0136] In n (where n is plural) orthogonal aberration modes Mi (i= 1 to n), the hologram 39 generates $\pm 1^{st}$ order light in respectively different directions. For the $\pm 1^{st}$ order light corresponding to each mode Mi, a bias aberration of +BiMi is imparted to $+1^{st}$ order light and a bias aberration of -BiMi to -1st order light, given a predetermined bias coefficient Bi.

[0137] The lens 40 converges n pairs of light beams, which have been deflected by the hologram 39, onto the photodetector 41. Assuming that the lens 40 has a focal length f, the hologram 39 and the photodetector 41 are each disposed in a position at the distance f from the principal plane of the lens 40, and the lens 40 functions as a Fourier

transform lens.

[0138] With respect to each of the n pairs of light beams, the photodetector **41** generates differential output signals Si, which are intensity signals of $\pm 1^{st}$ order light, and output them to the control section **42**. A differential output signal Si corresponding to an aberration mode Mi is a signal corresponding to a size Ai of the aberration mode Mi. A sensitivity Si/Ai with respect to the aberration mode Mi is predetermined according to design parameters such as the bias coefficient Bi.

[0139] A differential output signal Si represents wave front information, such that the amplitude of the differential output signal Si represents the wave front state of the light beam. A differential output signal S_1 is an output signal concerning a spherical aberration mode associated with changes in the substrate thickness of the disk **37**. A differential output signal S_2 is an output signal concerning an aberration mode mainly corresponding to a coma associated with a tilt of the disk **37** in a radial direction. A differential output signal S_3 is an output signal

concerning an aberration mode mainly corresponding to a coma associated with a tilt of the disk 37 in a tangential direction. The differential output signal S_4 is an output signal concerning the aberration mode of the objective lens 36 due to defocusing. A differential output signal S_5 is a signal which has been modulated by the prepits and recording marks on the disk 37.

[0140]   The control section 42 causes the movable section 7 to be displaced in accordance with the wave front information represented by the differential output signals Si. The control section 42 includes a wave front calculation section 43, a lens shift correction calculation section 44, an overall control section 45, and a wave front correction control section 46. In a preferable embodiment, the control section 42 or a portion thereof is provided on the base 1 of the microactuator array 35, and the control section 42 and the microactuator array 35 are implemented as a single chip.

[0141]   In another preferable embodiment, the light source 31, the collimator lens 32, the polarization beam splitter 33, the 1/4 wavelength plate 34, the microactuator array 35,

the objective lens **36**, the objective lens actuator **38**, and the wave front information generation section **47** are disposed on an optical pickup base (not shown). In this case, the optical pickup base may double as the base **1**. Moreover, the control section **42** or a portion thereof may be provided on the optical pickup base.

[0142] The wave front calculation section **43** calculates a phase function $\psi(x,y)$ for correcting a wave front aberration associated with a change in the substrate thickness of the disk **37** and its tilt, by using the differential output signals S_1 to S_3. Herein, x and y are coordinates corresponding to a mirror position in the microactuator array **35**.

[0143] The lens shift correction calculation section **44** receives the value of a lens shift amount x_0 of the objective lens **36** from the overall control section **45**, and based on this, converts the phase function $\psi(x,y)$ into $\psi(x-x_0,y)$. This $\psi(x-x_0,y)$ serves as a target wave front when the wave front correction control section **46** controls the microactuator array **35**.

【0144】 Based on the differential output signals S_4 and S_5, the overall control section 45 generates a focusing control signal Fo and a tracking control signal Tr, and outputs them to the objective lens actuator 38. Moreover, the overall control section 45 calculates the lens shift amount x_0 of the objective lens 36 by allowing the generated tracking control signal Tr to pass through a low-pass filter.

【0145】 From the lens shift correction calculation section 44, the wave front correction control section 46 receives a signal representing ψ $(x-x_0,y)$, and generates a control signal D for controlling the displacement of each movable section 7 of the microactuator array 35 in accordance with ψ $(x-x_0,y)$.

【0146】 The microactuator array 35 includes 42 $\times$ 36 microactuators 10, for example. In this case, since each microactuator 10 includes three stationary electrodes 4a to 4c, the microactuator array 35 includes $42 \times 36 \times 3$ stationary electrodes. The control signal D represents the size of each driving voltage to be individually supplied to each of the 42 $\times 36 \times 3$ stationary electrodes. In accordance with a target

displacement amount for a point of application of the driving force which is exerted on the movable section **7** by a stationary electrode receiving the control signal D, the wave front correction control section **46** sets the size of the driving voltage to be supplied to that stationary electrode. Moreover, the wave front correction control section **46** sets the size of the driving voltage in multiple steps, so that the point of application is capable of displacement in multiple steps of three or more (e.g., 128 steps=7 bits). Moreover, since a non-linear relationship generally exists between the driving voltage supplied to a stationary electrode and the displacement of the movable section **7**, it is possible to perform a correction process for obtaining linear displacement by allowing the control signal D to have a high resolution (e.g., 10 bits). The control signal D is to be switched in time series.

[0147] Assuming that there are n steps in the target displacement amount at each point of application in the movable section **7**, if the degree of non-diagonality δ'/δ is 1/n or less, the wave front correction control section **46**

does not need perform any correction for the displacements associated with non-diagonality, so that the control structure can be made very simple. Since the degree of non-diagonality δ'/δ is small in the microactuator **10** of the present invention, the control structure can be simplified even when a large number (e.g., $42 \times 36 \times 3$) of stationary electrodes are present. If the degree of non-diagonality δ'/δ is large as in the conventional microactuator 1000 (FIG. **10**), the calculation amount for correcting displacements associated with non-diagonality becomes huge, and the control structure becomes complicated, thus resulting in a tremendous increase in cost and a decrease in the driving speed of the microactuator. According to the present invention, the calculation amount for correcting displacements associated with non-diagonality can be very small, so that cost reduction and enhancement of the driving speed of the microactuator can be realized. The present invention is especially useful in the case of driving a large number of microactuators.

[0148] In the case where correction for displacements

associated with non-diagonality is to be performed, an operation of multiplying the target displacement amount for each point in the movable electrode 6 by an inverse matrix of the matrix on the right-hand side of (eq. 13) may be performed to determine driving forces to be generated by the stationary electrodes 4a to 4c, and driving voltages may be determined from the determined driving forces, thus generating the control signal D. Even in this case, since the non-diagonality of each microactuator 10 is already smaller than conventionally, it is easy to obtain a high correction accuracy, and the deterioration in the accuracy of non-linear correction due to fluctuations in the characteristics of the actuators is small, too. Moreover, in the case where each microactuator 10 satisfies:

$2 \leqq R^2 \cdot kz/krx$; and

$2 \leqq R^2 \cdot kz/kry$,

even if the aforementioned inverse matrix calculation is performed, each driving force will find its solution in a positive (pulling direction) range of values. Therefore, even in the case where a driving force which can only occur

in a pulling direction, e.g., electrostatic force, is employed, the wave front correction control section **46** can easily perform correction for displacements associated with non-diagonality.

[0149]   Next, with reference to FIG. 8A to FIG. 9B, coordinate positions of points of application in the movable section **7** that will make for an improved wave front approximation accuracy will be described. Each of points of application **A** to **C** on the movable section **7** is a point on an axis which extends through the center of a region of the corresponding stationary electrode among the stationary electrodes **4a** to **4c** where the driving force occurs and which is perpendicular to that stationary electrode. The center of a region in which a driving force for a single stationary electrode occurs coincides with the center of that stationary electrode, for example.

[0150]   The microactuator **10** is capable of bi-axial tilt and mono-axial vertical displacement. Descriptions will be given in the following order: first, a one-dimensional model where mono-axial tilt and mono-axial vertical displacement

take place will be described, followed by a description of a two-dimensional model where bi-axial tilt and mono-axial vertical displacement take place.

[0151] FIG. 8A and FIG. 8B are explanatory diagrams of a one-dimensional model representing the relationship between coordinate positions of points of application in the movable section 7 and wave front approximation accuracy.

[0152] First, with reference to FIG. 8A, a commonly-used line approximation method for a wave front will be described.

[0153] In FIG. 8A, the horizontal axis represents coordinate positions of the microactuator 10 in the x direction, whereas the vertical axis represents the phase of a wave front. A phase function ψ which serves as the correction target is shown by a chain double-dashed line. As already described, the phase function ψ is given as a function of the coordinate position x. Since the mirror section 6b is controllable in terms of displacement and tilt with respect to the base 1, the phase function ψ is to be reproduced through line approximations. It is assumed that the pitch between adjoining mirror sections 6b is P. By

taking a coordinate point x_j (where j is an integer) for each

pitch P, and connecting between the values $\psi(x_j)$ and $\psi(x_{j+1})$

of the phase function ψ for two adjoining coordinate points

x_j and x_{j+1}, the displacements and tilts of the mirror section

6b can be determined. These approximation lines ψ' are

shown with solid lines. Although this method only requires a

small amount of calculation and allows for a fast calculation

process, it will result in a large wave front error.

[0154] As another line approximation method, for each

section $[x_j, x_{j+1}]$, a displacement and tilt that minimizes the

error from the phase function ψ can be determined by a least

squares method. With this method, the wave front error can

be reduced, but the calculation amount increases.

[0155] With reference to FIG. **8B**, a line approximation

method for a wave front that will make for an improved

correction accuracy with a small calculation amount will be

described. Herein, two coordinate points $x_{j,a}$ and $x_{j,b}$ are

taken within a section $[x_j, x_{j+1}]$. The coordinate points $x_{j,a}$

and $x_{j,b}$ are at symmetric positions with respect to the

central portion O_j of the movable section **7**, and are both in

76

a position at a distance L from the central portion O_j. It will be discussed how a light reflecting surface can be defined as a line segment extending through two points, i.e., coordinates ($x_{j,a}$, $\psi(x_{j,a})$) and ($x_{j,b}$, $\psi(x_{j,b})$), by setting the value of the distance L to an appropriate value.

[0156]   FIG. 8C is a diagram showing a plotted relationship between the radius of curvature ρ of the phase function ψ in the section [x_j, x_{j+1}] and the value of the distance L that minimalizes the wave front error. It is assumed that the length of the mirror section **6b** is substantially equal to the pitch P. A nondimensionalized radius of curvature ρ/P is taken on the horizontal axis, whereas a nondimensionalized distance L/P that will minimalize the wave front error is taken on the vertical axis. The wave front error is defined as a square root of $\int(\psi - \psi')^2 dx$, a definite integral value of the error--raised to the second power--in a mirror having a length P. Although the radius of curvature ρ of the phase function ψ may take any arbitrary value, it can be seen from FIG. **8C** that the nondimensional distance L/P that minimalizes the wave front error hardly depends on the nondimensional

77

radius of curvature ρ/P, but takes a constant value of about 0.29. Therefore, by ensuring that the coordinate points $x_{j,a}$ and $x_{j,b}$ (where it is set that the distance L=0.29P) coincide with the coordinate positions of the points of application in the movable section 7, and that the displacement target values at the respective drive points are $\psi(x_{j,a})$ and $\psi(x_{j,b})$, it becomes possible to minimalize the wave front error to the same extent as in the method using a least squares method. Moreover, the displacement target values for points of application in the movable section 7 can be further directly calculated from the phase function ψ, and thus the calculation amount can be drastically reduced.

【0157】 With reference to FIGS. 9, a case will be described where the aforementioned line approximation method for a wave front that makes for an improved correction accuracy with a small calculation amount is applied to a two-dimensional model. FIGS. 9 are explanatory diagrams of a two-dimensional model representing the coordinate positions of points of application in the movable section 7 and the wave front approximation accuracy.

[0158]   FIG. 9A is a plan view schematically showing the microactuator array 35.   The pitch between adjoining mirror sections 6b is P.   Herein, it is approximated that the length Q of each side of the mirror section 6b is equal to $(P/\sqrt{3})$, and the gap between adjoining mirror sections 6b is ignored.

[0159]   FIG. 9B is a diagram showing a plotted relationship between the radius of curvature ρ of the phase function ψ in the mirror section 6b and the value of the distance R that minimalizes the wave front error.

[0160]   In FIG. 9B, a nondimensionalized radius of curvature ρ /P is taken on the horizontal axis, whereas a nondimensionalized nondimensional distance R/P that will minimalize the wave front error is taken on the vertical axis.   The wave front error is defined as a square root of $\int$ $\int (\psi - \psi ')^2 dxdy$, a definite integral value of the error-- raised to the second power--in the plane of a regular hexagon mirror plane.

[0161]   The results in the case where the phase function ψ represents a sphere are shown by solid lines.   It can be seen that the nondimensional distance R/P that will minimalize the

wave front error hardly depends on the nondimensional radius of curvature ρ/P, but takes a constant value of about 0.37. Moreover, the results in the aforementioned one-dimensional model are also shown with dotted lines. These results substantially correspond to the case where the phase function ψ represents a cylindrical surface which has a curvature only in the x direction but has no curvature in the y direction, but, as has already been described, the nondimensional distance R/P is about 0.29. If the case where the phase function ψ represents a sphere is defined as an oblateness of 0 and the case where the phase function ψ represents a cylindrical surface is defined as an oblateness of 1, a usual wave front has an intermediate oblateness therebetween. Therefore, it will be seen that the range of the nondimensional distance R/P can be set to no less than 0.29 and no more than 0.37, as shown in the hatched portion in the figure.

[0162] Thus, by ensuring that the distance R and the pitch P satisfy the relationship of:

$$0.29 \leq R/P \leq 0.37,$$

the approximation accuracy of the wave front error can be enhanced.

[0163] Since it is assumed that R=37 μm, P=110 μm in the present embodiment, the value of R/P is 0.336, thus satisfying the relationship of:

0.29 $\leqq$ R/P $\leqq$ 0.37.

Since the respective constituent elements are of such relative positioning, the displacement target values of the points of application **A** to **C** can be determined through direct calculations, by inputting the coordinate position (x,y) of each point of application to the phase function ψ. The amount of calculation to be performed by the wave front correction control section **46** can be drastically reduced.

INDUSTRIAL APPLICABILITY

[0164] A microactuator and an apparatus incorporating microactuators according to the present invention can be suitably used in the fields of optical devices and optical disk apparatuses which perform aberration correction, optical scanning, spectroscopy, and the like. They are also suitably

used in fields such as high-frequency circuits (e.g., tunable capacitors), flow control devices (e.g., variable flow paths), and biotechnology.